A survey of MHD waves in the magnetosheath: International Solar Terrestial Program observations

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Abstract. We present case and statistical studies of magnetohydrodynamic (MHD) fluctuations observed by the Wind and Geotail spacecraft in the Earth's dawn and dusk magnetosheath. A case study with simultaneous IMP 8 interplanetary magnetic field observations confirms theoretical predictions that most of the fluctuations originate in the solar wind rather than at the magnetopause and that the fluctuations can be almost absent from the outer magnetosheath. A second case study indicates that northward plasma velocity perturbations observed in the prenoon magnetosheath correspond to southward velocity perturbations in the postnoon magnetosheath, implying that the MHD perturbations apply a torque to the magnetosphere. A statistical survey reveals that the fluctuations almost invariably propagate antisunward in the magnetosheath, independent of their propagation direction relative to the interplanetary magnetic field.

1. Introduction

Fluctuations on timescales of minutes to hours are common in the solar wind. Within the framework of magnetohydrodynamics (MHD), the fluctuations can be categorized as shocks, tangential discontinuities, and fast, slow, and intermediate (Alfvénic) mode waves. Alfvénic fluctuations can be distinguished from the others because they exhibit proportional magnetic field and plasma flow perturbations in the absence of any significant density or magnetic field strength variations.

As in the case of fast and slow mode waves, the Alfvénic field and flow perturbations are negatively correlated for fluctuations propagating along the magnetic field and positively correlated for fluctuations propagating opposite the magnetic field. For Alfvénic fluctuations, the relationship can be expressed as $dV = \pm 21.8 dB/(1.4n)^{0.5}$, where V is the velocity (km s^{-1}), B is the magnetic field (nanoteslas), n is the number density (cm^{-3}), and we have assumed that alpha particles constitute 10% of the solar wind number density. The constant of proportionality can be significantly smaller for compressional slow mode perturbations with anticorrelated density and magnetic field strength variations but significantly larger for fast mode perturbations with correlated density and magnetic field strength perturbations. Near Earth, correlation coefficients for the solar wind magnetic field and plasma flow velocity perturbations exceed 0.6 at least 50% of the time, the constant of proportionality lies near 21.8, corresponding density and magnetic field strength variations are often absent, and almost all the fluctuations propagate outward from the Sun, indicating the frequent presence of Alfvénic fluctuations in the solar wind [*Belcher and Davis*, 1971].

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Several theoretical studies have treated the interaction of Alfvénic fluctuations with the Earth's bow shock. One-dimensional simulations indicate that Alfvénic fluctuations striking the Earth's bow shock launch a set of sunward and antisunward propagating fast, intermediate, and slow mode waves [e.g., *Völk and Auer*, 1974]. The sunward propagating fast mode wave becomes the new bow shock, whereas the plasma flow sweeps the other sunward and antisunward propagating waves antisunward through the magnetosheath. If the amplitude of the transmitted fluctuations exceeds that of the reflected fluctuations, one might naively suppose that the fluctuations would continue to propagate through the magnetosheath in the same direction relative to the magnetic field as in the solar wind.

More recently, *Cable and Lin* [1998] reported the results of a three-dimensional MHD simulation for the interaction of solar wind Alfvénic fluctuations with the Earth's bow shock. During (typical) periods of spiral interplanetary magnetic field (IMF) orientation, the simulation predicts the presence of antisunward propagating fluctuations within the inner prenoon and postnoon magnetosheath, but only weak fluctuations within the outer magnetosheath. It is important to note that the fluctuations in the magnetosheath are no longer strictly Alfvénic: the velocity and magnetic field do not vary precisely in phase or antiphase, and the cross correlation between these parameters falls to values below unity.

As shown in Figure 1, draping causes the x component of the magnetosheath magnetic field to reverse across both the prenoon bow shock and local noon [*Fairfield*, 1967]. If the fluctuations continue to propagate antisunward through both the dawn and dusk magnetosheath, then their sense of propagation relative to the magnetic field must reverse across both the prenoon bow shock and across local noon, in contrast to the naïve expectation mentioned above. We can therefore infer that the plasma velocity perturbations reverse across the prenoon bow shock and across local noon in the magnetosheath.

Sibeck et al. [1997] reported a case study of simultaneous Wind solar wind and Geotail magnetosheath observations consistent with a reversal in flow directions across the bow shock. They showed that individual magnetic field fluctuations observed by Geotail within the prenoon magnetosheath could be directly related to similar features observed upstream by Wind.
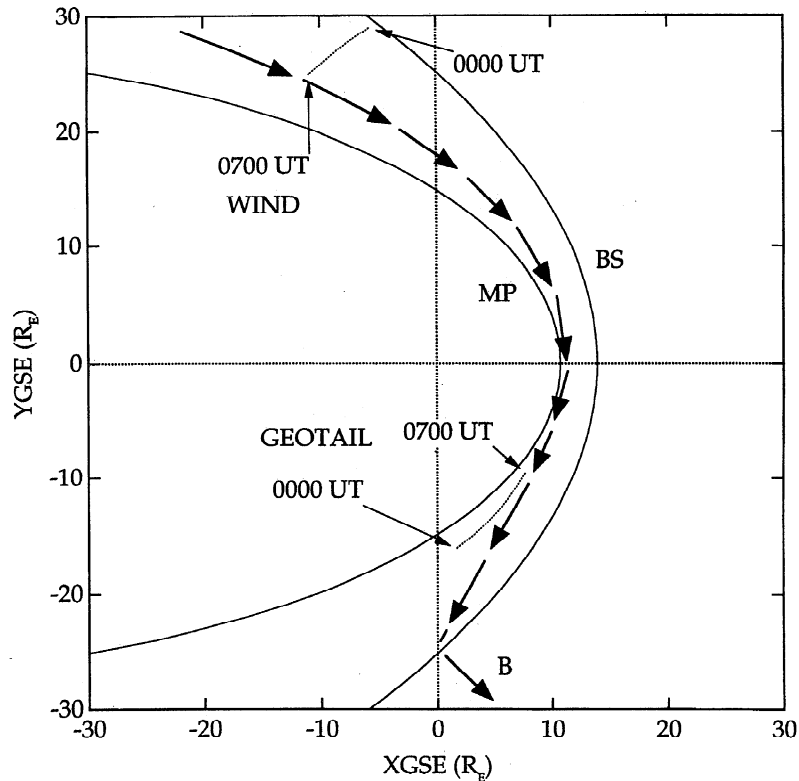
Figure 1. Trajectories of the Geotail and Wind spacecraft from 0000 to 0700 UT on December 30, 1996. The dashed line shows a representative magnetic field line with a spiral IMF orientation draped against the magnetosphere.

Whereas the plasma and magnetic field perturbations were positively correlated at Wind, they were anticorrelated at Geotail. Consequently, northward flow perturbations at Wind corresponded to southward flow perturbations at Geotail. This paper presents case and statistical studies that demonstrate that velocity fluctuations in the magnetosheath originate in the solar wind, move antisunward, and reverse across local noon.

2. Fluctuation Reversal Across Local Noon

We begin by presenting a case study of simultaneous Wind and Geotail magnetosheath observations from 0000 to 0700 UT on December 30, 1996. Figure 1 shows the trajectories of Wind and Geotail in the context of the expected locations of the bow shock and magnetopause for the 5-nPa solar wind dynamic pressure and a 0-nT IMF B_z component observed during several Wind entries into the solar wind during this interval. During the 7-hour interval, Wind moved inward through the dusk magnetosheath from GSE $(x, y, z) = (-5.6, 29.1, -2.6)$ to $(-11.1, 24.8, -1.6)$ R_E, whereas Geotail moved sunward through the dawn magnetosheath from GSE $(x, y, z) = (1.5, -16.2, 0.1)$ to $(7.2, -9.3, 0.8)$ R_E. The location and shape of the magnetopause have been taken from the empirical study of *Roelof and Sibeck* [1993] for the specified solar wind conditions, whereas the bow shock is that of *Fairfield* [1971] scaled to the dynamic pressure.

The first two panels of Figure 2 present the GSE x and y components of the magnetic field observed by the magnetic field (MGF) [*Kokubun et al.*, 1994] and Magnetic Fields Investigation (MFI) [*Lepping et al.*, 1995] instruments on the Geotail

and Wind spacecraft at 64 and 46 s time resolution, respectively. Throughout most of the interval shown, both spacecraft recorded a dawnward (negative) IMF B_y component. Whereas Wind generally observed a sunward (positive) IMF B_x component, Geotail generally observed an antisunward (negative) IMF B_x component. As illustrated in Figure 1, the similarity of the B_y components at both spacecraft and the discrepancy between the B_x components are consistent with the expected effects of magnetosheath magnetic field draping at the postnoon and prenoon positions of the spacecraft during periods of toward sector IMF.

According to the predictions of the Cable-Lin model, MHD fluctuations should propagate antisunward in both the prenoon and postnoon magnetosheath. For the particular example shown in Figures 1 and 2, the fluctuations should propagate parallel to the magnetic field in the prenoon magnetosheath (antiphase relationship expected between the magnetic field and plasma flow perturbations), but antiparallel to the magnetic field in the postnoon magnetosheath (in-phase relationship expected between the magnetic field and plasma flow perturbations).

The third and fourth panels of Figure 2 present the GSE z components of the Geotail Low Energy Particle Instrument (LEP) [*Mukai et al.*, 1994] ion flow velocity and the MGF magnetic field at 64 s time resolution. For comparison, the dashed trace in the third panel shows the Alfvénic velocity predicted on the basis of the magnetic field and density fluctuations observed by Geotail during this interval. The close, but antiphase, correspondence between the predicted and observed fluctuations indicates that Geotail observed antisunward propagating fluctuations on antisunward pointing magnetic field lines
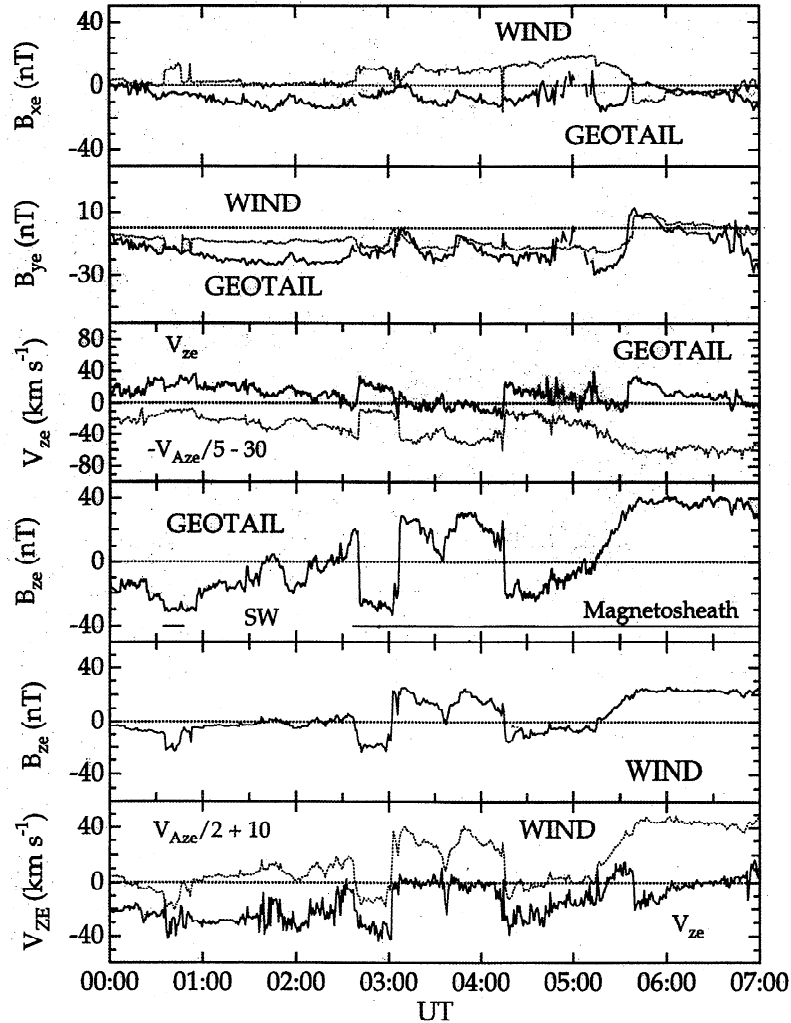
Figure 2. A comparison of Geotail and Wind plasma and magnetic field observations (December 30, 1996) in the dawn and dusk magnetosheath, respectively. Note that Geotail and Wind velocities (dashed lines) have been reduced by factors of 5 and 2, respectively.

at its location in the prenoon magnetosheath, as predicted by the Cable-Lin model. Note that the observed amplitudes were a factor of 5 less than those predicted for Alfvénic fluctuations. We encountered a similar problem in our previous study [*Sibeck et al.*, 1997] but attributed it to instrumental problems. It now appears certain that the constant of proportionality is invariably smaller in the magnetosheath than that predicted for Alfvénic fluctuations, implying the presence of slow mode compressional fluctuations.

The fifth and sixth panels of Figure 2 present the GSE z components of the Wind MFI magnetic field and three-dimensional plasma (3DP) [*Lin et al.*, 1995] ion flow velocity at 46 s time resolution. Combined plasma and magnetic field observations indicate that Wind was in the dusk magnetosheath from 0035 to 0045 UT and from 0240 to 0700 UT (see region identification bar in the fifth panel). For comparison, the dashed trace in the third panel shows the Alfvénic velocity predicted on the basis of the magnetic field and density fluctuations observed by Wind during this interval. The in-phase relationship between the predicted and observed fluctuations indicates that Wind observed antisunward propagating fluctuations on sunward pointing magnetic field lines at its location in the postnoon magnetosheath, as predicted by the Cable-Lin model.

Note that the observed amplitudes were a factor of 2 less than those predicted, implying slow mode rather than Alfvénic fluctuations.

The scatterplots shown on the right of Figure 3 illustrate the positive correlation between all three components of the magnetic field and ion velocity perturbations at Wind, as required for antisunward propagating MHD fluctuations in the antisunward pointing postnoon magnetosheath magnetic field. By contrast, the correlations are negative for the Y and Z components at Geotail, as required for antisunward propagating MHD fluctuations in the sunward pointing prenoon magnetosheath magnetic field.

The scatterplot for the X components at Geotail indicates a positive correlation, although the range of values observed is not large and most of the points lie highly clustered in comparison with all the other scatterplots. As discussed below, our survey revealed several other examples of contradictory correlation coefficients, with the higher correlation coefficients corresponding to the predicted sense of wave propagation. There is one further discrepancy in the scatterplots. The correlation between V_z and B_z at Geotail becomes positive for values of B_z in excess of 30 nT. The observations shown in Figure 2 indicate that this occurs after 0530 UT when the B_x component dimin-
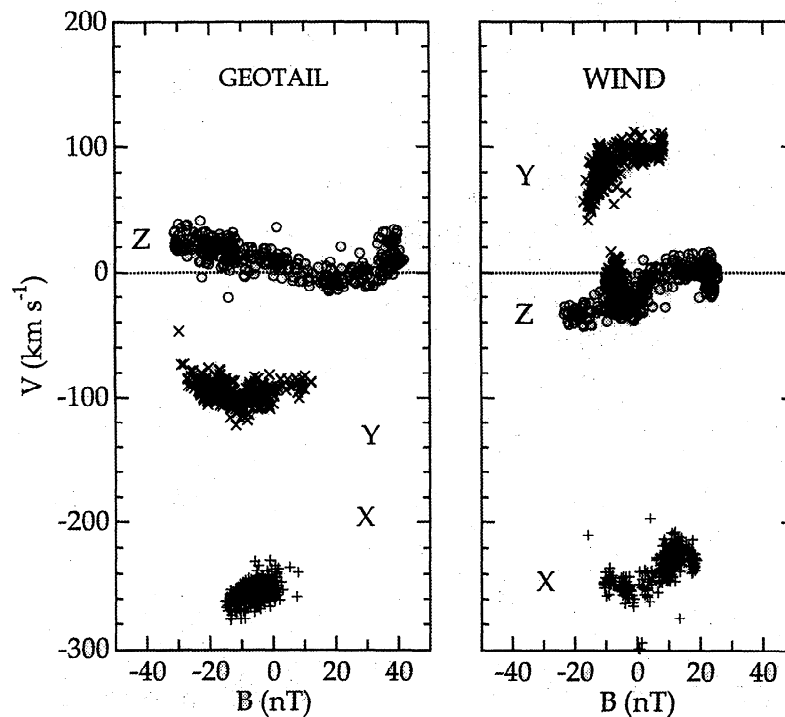
Figure 3. Scatterplots of the velocity versus the magnetic field in GSE components observed by Geotail and Wind from 0000 to 0700 UT on December 30, 1996.

ishes to a value near 0 nT and it is not possible to define the downstream direction.

Because observed sheath flow perturbations have much smaller amplitudes than those predicted for Alfvénic fluctua-

tions, we have attributed them to slow mode waves. Anticorrelated variations in the density and magnetic field strength are another attribute of slow mode waves. Figure 4 presents the density and magnetic field strength observed by
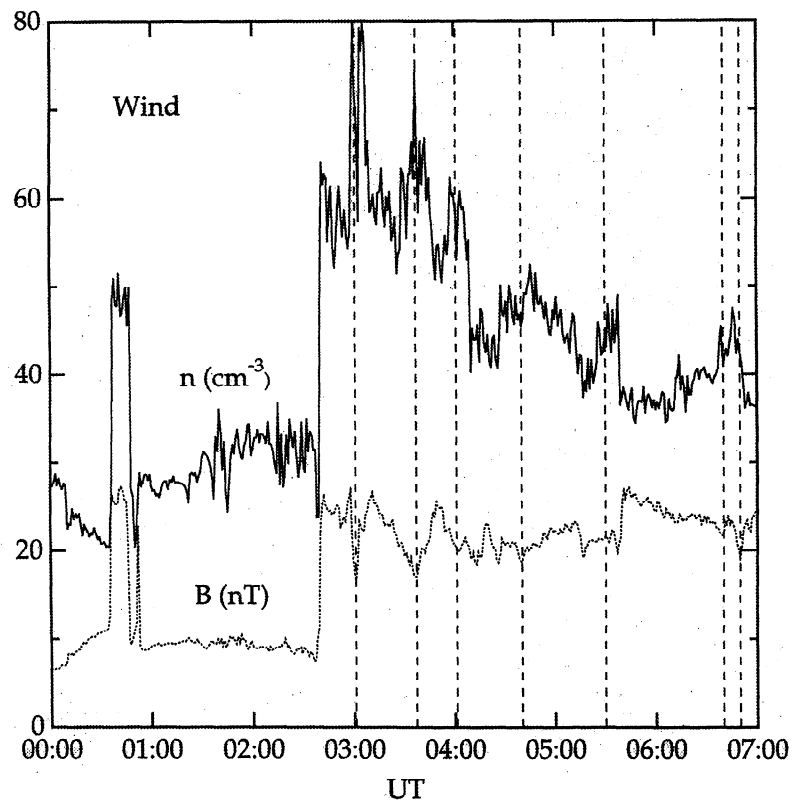

Figure 4. A comparison of the Wind density and magnetic field strength from 0000 to 0700 UT on December 30, 1996.

Wind during the period from 0000 to 0700 UT on December 30, 1996. Enhanced densities and magnetic field strengths distinguish the magnetosheath intervals from 0035 to 0045 and 0240 to 0700 UT from the solar wind. Vertical dashed lines indicate the times of at least seven significant density increases during the second magnetosheath interval. Most density increases corresponded to depressed magnetic field strengths, as required for slow mode waves.

Returning to Figure 2, note that although the B_z traces for Geotail and Wind resemble each other, the V_z traces at these two spacecraft are essentially inverted. We have seen a similar event, with the positions of Geotail and Wind reversed on June 12, 1997. Consequently, the interaction of an Alfvénic fluctuation with the bow shock results in the magnetosheath flow applying a torque to the magnetosphere: southward flow variations on the dawn flank correspond to northward flow variations on the dusk flank, and vice versa.

Finally, *Cable and Lin* [1998] mentioned the possibility that the sense of the correlation might vary from the outer dusk magnetosheath to the inner dusk magnetosheath or that the correlation might be nearly absent in the outer magnetosheath. Figure 2 provides no evidence for this phenomenon. Instead, we find a single sense of correlation (positive) between the field and flow perturbations throughout the entire postnoon magnetosheath during this event.

3. Fluctuations in the Dusk Magnetosheath

Petrinec et al. [1997] recently presented several case studies of plasma and magnetic field fluctuations observed by Geotail in the dawn and dusk magnetosheath. They divided the observed fluctuations into two categories: those in which antisunward flow speeds exceeded the simultaneous solar wind velocity and those in which they did not. Events in the former category were observed in the predawn magnetopause current layer during periods of sunward magnetosheath magnetic field orientation. The current layer was marked by densities slightly less than those in the magnetosheath, temperatures slightly greater, and weak antisunward magnetic fields. These flows were attributed to some process on the southern lobe magnetopause, for example, reconnection, the Kelvin-Helmholtz boundary instability, or escaping higher-energy low-latitude boundary layer plasma.

Events in the latter category were observed within the inner dusk magnetosheath and attributed to Alfvén mode waves launched by the magnetosphere and standing in the solar wind/ magnetosheath flow. Further consideration of the locations where the fluctuations were observed, their sense of propagation relative to the magnetic field, and corresponding features in simultaneous IMP 8 solar wind observations suggest an alternative explanation of these events in terms of the more recent Cable-Lin model.

Geotail observations from 0315 to 1325 UT on March 29, 1995, were the focus of the *Petrinec et al.* [1997] study. During this interval, Geotail moved inward through the postnoon magnetosheath from GSE $(x, y, z) = (-7.0, 27.0, -3.4)$ to $(-12.0, 22.1, -2.6)$ R_E. Petrinec et al. reported that the Alfvénic fluctuations on March 29, 1995, could be observed only toward the end of this interval within the inner, and not the outer, dusk magnetosheath. This observation is consistent with the Cable-Lin model, which predicts a substantial correlation between flow velocity and magnetic field variations in the inner dusk magnetosheath but almost no correlation in the outer dusk magnetosheath. *Petrinec et al.* [1997] interpreted the fluc-
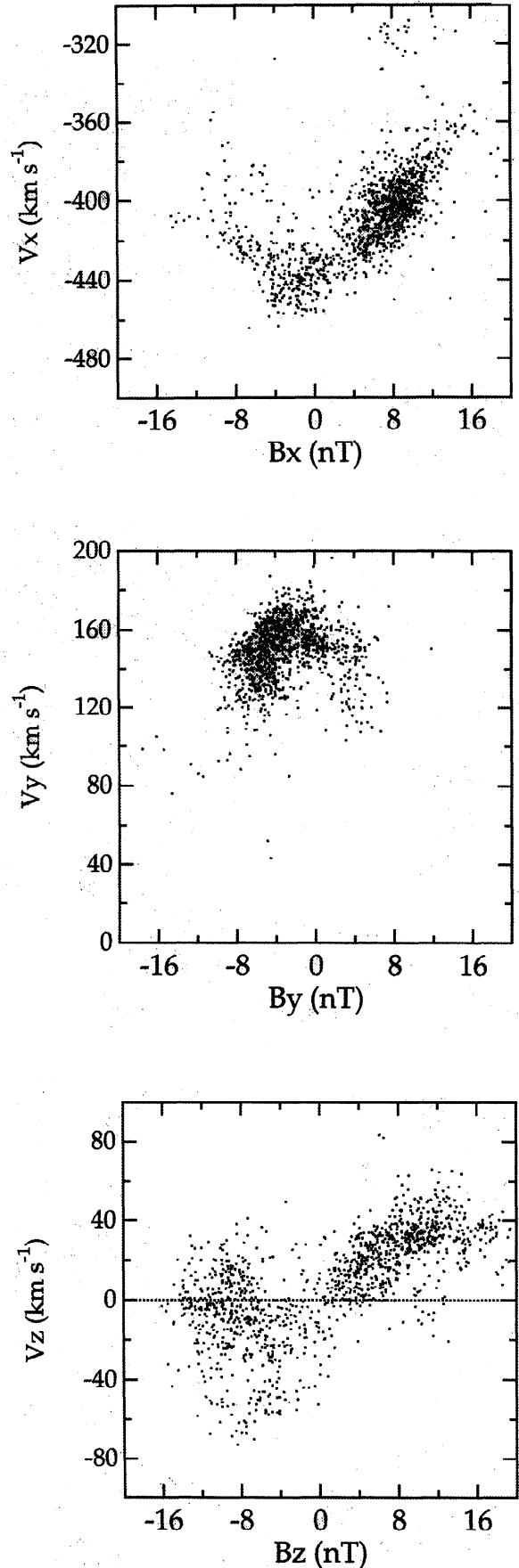

Figure 5. Scatterplots of the velocity versus the magnetic field in GSE coordinates observed by Geotail from 0900 to 1300 UT on March 29, 1995.

tuations in terms of an Alfvénic wave front launched sunward from the magnetosphere and standing within the magnetosheath. However, the phase relationships between the plasma and magnetic field variations that they reported were consistent with the antisunward propagating fluctuations predicted by the Cable-Lin model. Figure 5 presents scatterplots of the GSE x, y, and z components of the velocity versus the same components of the magnetic field for the interval studied by Petrinec et al. As required for antisunward propagating fluctuations, the velocity and magnetic field perturbations were positively correlated when the magnetic field points sunward ($B_x > 0$) and negatively correlated when the magnetic field points antisunward ($B_x < 0$).

If the fluctuations originated in the solar wind rather than at the magnetopause, there should be evidence for similar magnetic field variations in simultaneous IMP 8 solar wind observations during this interval. IMP 8 was located upstream of the bow shock and moved from GSE $(x, y, z) = (22.5, 26.0, 22.8)$ to $(17.8, 29.8, 21.7)$ R_E during the 10-hour interval. Figure 6 presents 3-s Geotail MGF magnetic field, 12-s Geotail LEP plasma, and 15.36-s IMP 8 magnetometer magnetic field observations for the period from 0900 to 1300 UT. Although lag times vary slightly in response to fluctuations in the solar wind/magnetosheath velocity, Figure 6 makes it clear that most features at Geotail correspond to equivalent features at IMP 8, that is, the fluctuations within the magnetosheath have a solar wind rather than a magnetospheric origin.

4. Statistical Study

We examined 3DP and MFI observations at 51-s time resolution on each Wind perigee pass. Tables 1 and 2 list each magnetosheath interval with more than 100 points. Sometimes the sense of the B_x component reversed during the course of a pass through the magnetosheath. When the number of points with each orientation exceeded 100, both are listed. Figure 7 shows a projection of the Wind trajectories in the GSE x-y plane during each of the 13 passes through the dawn magnetosheath and the 16 passes through the dusk magnetosheath.
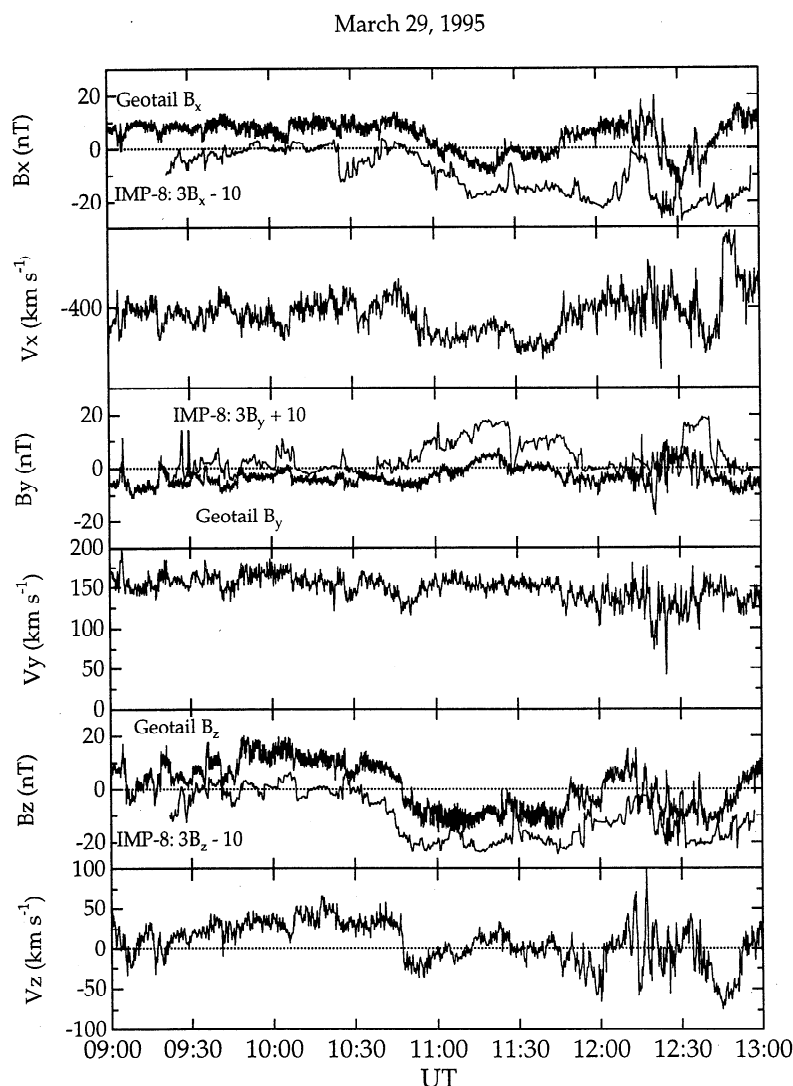
March 29, 1995

Figure 6. A comparison of IMP 8 IMF observations with corresponding Geotail magnetosheath magnetic field and plasma variations on March 29, 1995. The observations are presented in GSE coordinates, the IMP 8 observations have been lagged 660 s, and the amplitudes of the IMP 8 magnetic fields have been multiplied by a factor of 3 for comparison with the Geotail observations.

Table 1. Prenoon Passes

Pass	Date	Number	LT	B_x	B_x-V_x	B_y-V_y	B_z-V_z
						Correlations	
1	Jan. 1, 1997	256	3.5	>0	0.01	−0.05	0.12
	Jan. 1, 1997	373	3.5	<0	(−0.82)	−0.15	(−0.78)
2	Oct. 22, 1997	500	3.6	>0	−0.33	0.09	−0.07
	Oct. 22, 1997	817	3.6	<0	(−0.83)	(−0.50)	(−0.72)
3	May 10, 1996	169	4.6	>0	(0.53)	−0.03	0.28
4	Sept. 17, 1995	114	4.6	>0	[−0.68]	0.01	−0.28
	Sept. 17, 1995	149	4.6	<0	(−0.62)	−0.13	(−0.79)
5	Jan. 13, 1996	624	4.7	>0	(0.69)	0.25	(0.61)
6	Jul. 26, 1997	368	4.9	<0	−0.25	0.11	−0.16
7	Dec. 3, 1996	141	4.9	<0	−0.27	−0.25	−0.14
8	Dec. 22, 1995	172	5.3	>0	[−0.51]	−0.05	(0.91)
9	Oct. 5, 1996	235	5.3	<0	−0.35	−0.14	(−0.59)
10	Jul. 4, 1997	488	5.5	>0	−0.14	−0.12	(0.45)
	Jul. 4, 1997	201	5.5	<0	(−0.44)	(−0.57)	−0.35
11	Nov. 16, 1996	113	5.6	<0	[0.46]	0.22	0.01
12	Dec. 25, 1994	129	5.8	<0	−0.08	0.10	−0.16
13	Mar. 28, 1996	135	5.9	>0	[−0.49]	−0.16	−0.21

We correlated observed (**V**) and predicted (21.8 $d\mathbf{B}/(1.4n)^{0.5}$) plasma velocity perturbations during each of these passes to determine whether or not perturbations were present, and if so, in what direction they propagated relative to the magnetic field. We have entered the results, component by component, in Tables 1 and 2. Entries in parentheses indicate correlation coefficients in excess of 0.4 and consistent with antisunward propagating fluctuations. Entries in brackets indicate correlation coefficients in excess of 0.4 but consistent with sunward propagating fluctuations.

In general, we do not expect to observe high correlation coefficients. The Cable-Lin model does not predict them except in the immediate vicinity of the magnetopause. Wave-particle interaction processes at the bow shock introduce high-frequency variations that reduce the correlation coefficients. And some of the features observed within the magnetosheath correspond to tangential discontinuities rather than waves. If correlation coefficients in excess of 0.6 can be taken as evidence for the presence of fluctuations, then the fluctuations were present during 14 of 33 intervals. If the requirement is lowered to a correlation coefficient of only 0.4, then Alfvénic fluctuations were present on 23 of 33 intervals. These occurrence rates are roughly comparable with those seen in the solar wind.

Figure 7 portrays the results as a function of location. Magnetosheath passes with antisunward propagating fluctuations, as indicated by correlation coefficients in excess of 0.4, are marked by the letter A. Magnetosheath passes with sunward propagating fluctuations, as indicated by correlation coefficients in excess of 0.4, are marked by the letter S. The size of the letter indicates the magnitude of the correlation coefficient, ranging from small (>0.4), through medium (>0.6), to large (>0.8). No symbol is shown for correlation coefficients less than 0.4. Prenoon pass 8 was marked by correlation coefficients indicating both sunward (X component) and antisunward (Z component) propagating fluctuations and is therefore marked by the letter M for mixed.

The overall pattern seen in Figure 7 is one of antisunward propagation, particularly in the postnoon magnetosheath. By contrast, the situation in the prenoon magnetosheath is somewhat more complicated. Antisunward propagating fluctuations still predominate, but sunward propagating fluctuations are also present, particularly near the terminator. Given the typical spiral IMF orientation shown in Figure 1, the Wind observations suggest that at least some solar wind fluctuations succeed in crossing the prenoon bow shock to propagate sunward in the prenoon magnetosheath.

Table 2. Postnoon Passes

| Pass	Date	Number	LT	B_x	B_x-V_x	B_y-V_y	B_z-V_z
						Correlations	
1	Oct. 4, 1996	176	15.4	>0	0.22	−0.03	(0.66)
2	Sept. 11, 1996	130	16.5	<0	0.19	0.03	−0.24
3	Aug. 19, 1996	115	16.8	<0	−0.11	0.04	0.16
4	Aug. 1, 1995	247	17.4	<0	(−0.65)	(−0.45)	−0.37
5	Nov. 15, 1996	478	17.6	<0	−0.24	0.20	(−0.65)
6	Jul. 3, 1997	239	17.7	<0	−0.30	−0.31	(−0.93)
7	Dec. 20, 1995	481	17.8	>0	0.33	(0.44)	0.01
8	Jan. 12, 1996	283	18.0	>0	0.23	(0.64)	(0.58)
9	Dec. 2, 1996	196	18.0	<0	(−0.93)	(−0.83)	−0.25
10	Oct. 20, 1997	281	18.0	<0	(−0.51)	−0.25	−0.38
11	Sept. 29, 1997	252	18.3	<0	0.34	0.03	0.07
12	May 9, 1996	387	18.5	<0	−0.17	−0.18	−0.04
13	Nov. 28, 1995	277	18.9	<0	(−0.41)	−0.36	−0.30
14	Sept. 16, 1995	134	18.9	>0	0.14	0.05	−0.19
15	Apr. 17, 1996	368	19.1	>0	(0.53)	0.32	(0.84)
16	Dec. 30, 1996	249	19.4	>0	(0.59)	(0.51)	(0.69)
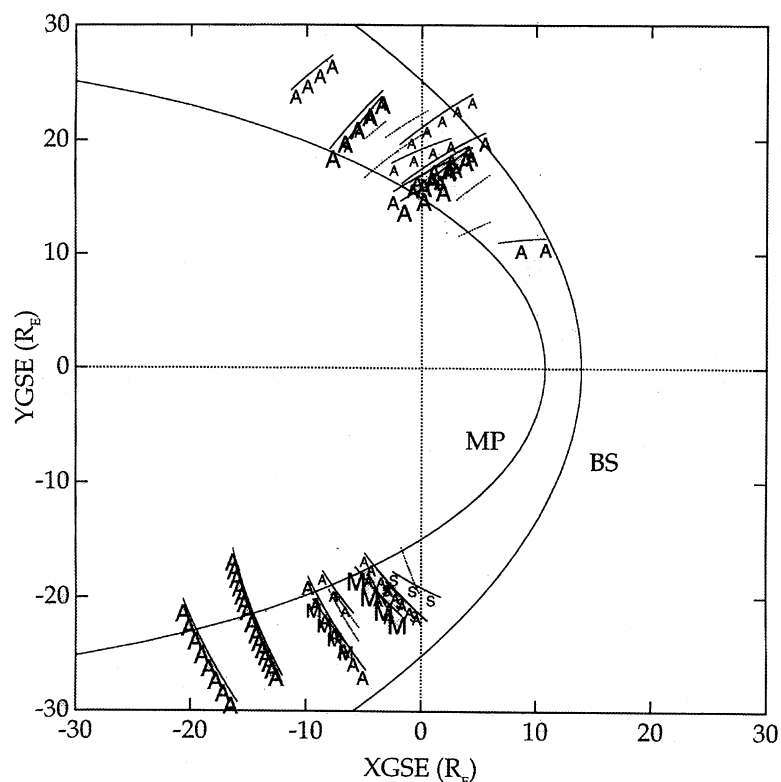
Figure 7. Wind perigee passes through the magnetosheath. Letters A, S, and M indicate passes on which antisunward, sunward, and mixed propagating waves were observed, respectively. The size of the letters indicates the magnitude of the correlation coefficient: large (>0.8), medium (>0.6), and small (>0.4).

5. Conclusions

MHD models predict that antisunward propagating Alfvénic fluctuations in the solar wind will generate antisunward propagating fluctuations in both the prenoon and postnoon magnetosheath but that the B_x component of the magnetosheath magnetic field will reverse across local noon. As a result, the fluctuations propagate parallel to the draped magnetic field on one side of local noon and antiparallel to the magnetic field on the other side of local noon. Since the magnetic field perturbations observed in the prenoon and postnoon magnetosheath resemble those in the solar wind, the velocity perturbations observed in the premagnetosheath and postmagnetosheath must be inverted.

We presented a case study of simultaneous Wind and Geotail magnetosheath observations that indicated a striking reversal in velocities across local noon, confirming the MHD model predictions. Because the amplitude of the observed velocity fluctuations was much less than that predicted for Alfvénic fluctuations, and antiphase density and magnetic field strength perturbations were present, we attributed the variations observed in the magnetosheath to slow mode waves launched by solar wind features striking the bow shock. The reason that the velocity perturbations were depressed by a factor of 5 prior to local noon, but only a factor of 2 after local noon, remains to be determined.

We then reexamined a previously reported case of Alfvénic fluctuations in the postnoon magnetosheath. As predicted by the Cable-Lin model, the fluctuations were present only within the inner magnetosheath, propagated antisunward, and corre-

sponded to features observed by IMP 8 in the solar wind. We then presented the results of a statistical survey of Wind observations in the dawn and dusk magnetosheath. MHD fluctuations were present in about half of the passes, and they almost invariably propagated antisunward. The fact that the sense of the flow variations varies across local noon implies that the interaction of Alfvénic fluctuations with the bow shock results in the application of a torque to the magnetosphere.

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